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Stilling Well Design for Accurate Water Level Measurement

by

William N. Seelig

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A method is presented for the design of stilling wells based on the work by Noye (1974a, 1974b, 1974c). A step-by-step procedure is outlined, design curves are presented, and an example is given to illustrate the procedure.

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PREFACE

This report provides coastal engineers with a method for designing stilling wells to accurately measure coastal water level fluctuations, based on the theoretical and laboratory work of Noye (1974a, 1974b, 1974c). The work was carried out under the coastal structures program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by William N. Seelig, Research Hydraulic Engineer, Coastal Structures Branch, under the general supervision of Dr. R.M. Sorensen, Chief, Coastal Structures Branch.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

John H. Cousins

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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FIGURES

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

STILLING WELL DESIGN FOR ACCURATE WATER LEVEL MEASUREMENT

by
William N. Seelig

I. INTRODUCTION

Coastal engineers and scientists have a frequent need for accurate measurements of long-period water level fluctuations (periods longer than about 5 minutes). Important long waves may include astronomical or meteorological tides, seiching of lakes and harbors, and tsunamis. The approximate distribution of ocean surface waves is shown in Figure 1.

A problem in measuring water level has been that the long-period wave of interest, the *signal*, is often of much smaller amplitude than the short-period wind waves that act as *noise*. For example, on the Great Lakes a seiche important to inlet hydraulics may have an amplitude on the order of 0.1 foot, while wind waves may be several feet high. In this type of situation where the signal-to-noise ratio is small, a carefully designed system is needed to dampen or eliminate noise while recording the important long waves.

This paper presents a method of designing a water level recording system for accurately measuring water level fluctuations of interest by dampening or eliminating undesirable short-period fluctuations. The unique aspect of this design is that water level fluctuations inside the well are linearly related to fluctuations outside the well, so no nonlinear water level amplifications occur.

The linear stilling well design presented requires that the well be free from fouling. Even a small piece of debris in the orifice will disrupt the response characteristics of the well, so this type of well is recommended for short-term operation in clear water areas.

II. LINEAR DAMPING STILLING WELLS

Noye (1974a), using laboratory tests, showed that the conventional stilling well, consisting of a well and orifice, will respond to a broad spectrum of waves and a response of this type may confuse the record of interest. Cross (1968) reported that this type of well system may introduce higher harmonics of waves into the well and that wind waves, through nonlinear effects, can cause a net displacement of the mean water level inside the well as compared with the mean water level outside the well.

A recommended stilling well system for accurately measuring long waves is the linear damping stilling well which has a pipe or tube as an orifice (Fig. 2) (Noye, 1974b, 1974c). This system can be designed to record the important long waves and eliminate undesirable noise.

A disadvantage of the system is the critical diameter of the intake pipe. Dirt or other foreign matter entering the pipe will disrupt calibrated response characteristics. For this reason, the intake to the well should be carefully sited, preferably in an area where fouling will not affect the operation of the well.

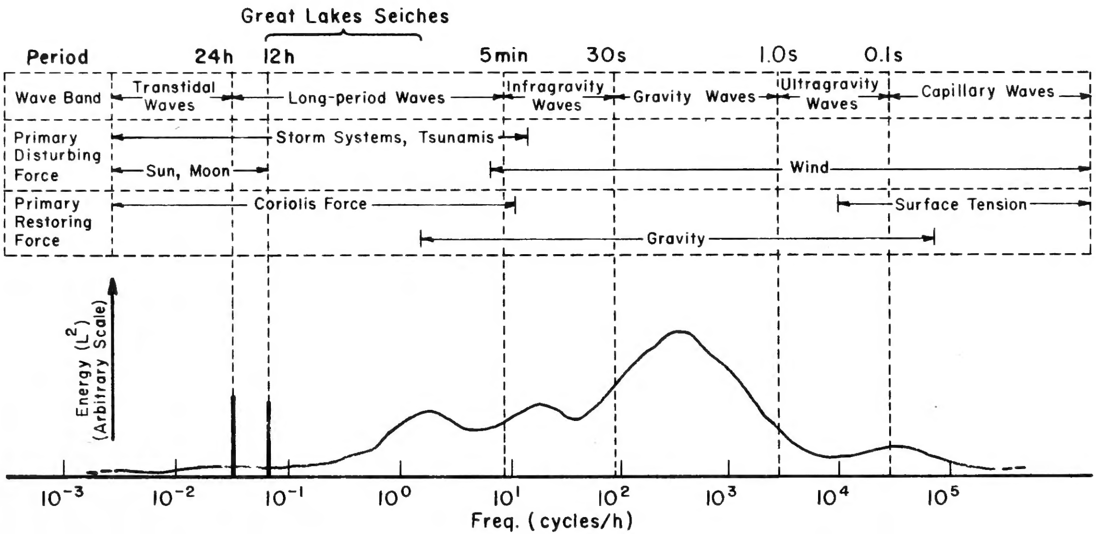

Figure 1. Approximate distribution of ocean surface wave energy illustrating the classification of surface waves by wave band, primary distributing force, and primary restoring force.

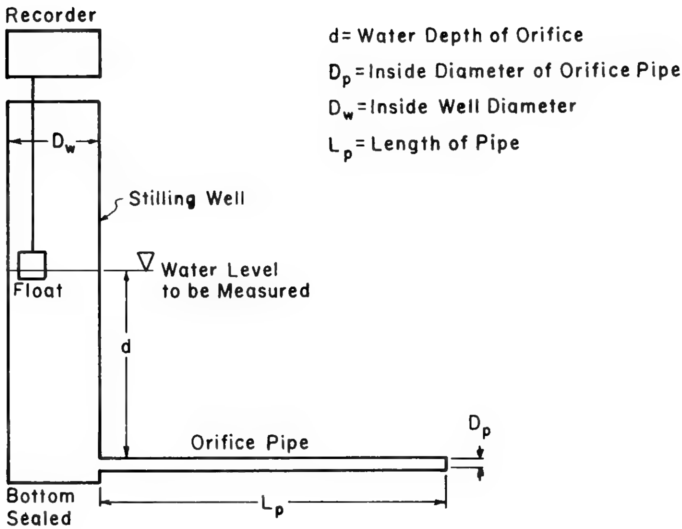

Figure 2. The linear stilling well.

The well is especially useful for short-term operations in measuring harbor response to long-wave forcing and long-wave conditions outside the harbor. On the Great Lakes, forced pumping mode oscillations near or longer than the natural pumping mode ("Helmholtz mode") of the inlet-harbor system are generally the most important in producing reversing inlet currents and harbor oscillations. If the gage is to be placed in a harbor and the geometry of the harbor and inlets are known, a formula can be used to predict the Helmholtz period (Seelig and Sorensen, 1976) or a simple numerical model can be used to show which long waves will be important to the harbor (Seelig, Harris, and Herchenroder, 1976). Typical Helmholtz periods for Great Lakes harbors range from 10 minutes to 5 hours. Once these potentially important periods have been determined, the stilling well system and recorder can be designed to record the waves.

The linear stilling well consists of two basic components: (a) A well of inside diameter, D_w, which provides the stillwater level to be measured; and (b) an orifice consisting of a pipe of length, L_p, and inside diameter, D_p. Both the well and pipe should be smooth and free of obstructions. Common materials are plastic or metal.

The bottom of the well is sealed so that the water can only enter the well through the orifice pipe. Friction in the pipe due to laminar flow, in conjunction with the continuity of flow between the small orifice pipe and the relativly larger well, determines how the stilling well will respond to long-wave forcing.

The variables that can be changed in well design are the diameter of the well, the diameter and length of the intake pipe, and the depth of the orifice pipe entrance below the water level. Noye (1974b, 1974c) has theoretically and experimentally shown that two dimensionless parameters (β_2 and N) can be used to design a linear stilling well. β_2 is a dimensionless frequency; N describes the amplitude modulation and phase lag of the long wave inside the well as compared with the wave outside the well. The parameters are given by Noye as:

$$N = \frac{128\ \nu^2\ L_p\ D_w{}^2}{g\ D_p{}^6} \tag{1}$$

and

$$\beta_2 = \left(\frac{32\ \nu\ L_p\ D_w{}^2}{g\ D_p{}^4}\right)\frac{2\pi}{T}\ , \tag{2}$$

where

ν = the kinematic viscosity of water (about 10^{-5} feet squared per second)

L_p = the pipe length (feet)

D_w = the inside diameter of the well (feet)

g = the acceleration of gravity (32.2 feet per second squared)

D_p = the inside diameter of the orifice pipe (feet)

T = the wave period (seconds).

The theoretical dimensionless response characteristics of the linear stilling well as functions of N and β_2 are shown in Figure 3. It is frequently best to design a well with a value of N greater than 5 because the well can be tested using a drainage test to determine the actual response characteristics of the well (Noye, 1974b). Wells with a value of N less than 5 are more difficult to test. A value of $N = 0.33$ gives the sharpest distinction between measured and dampened waves; however, this type of well is difficult to build of common materials and even more difficult to test. It is desirable to have $0 \leq \beta_2 \leq 0.4$ for the long-period waves to be measured so that the long-wave amplitude in the well is approximately equal to the long-wave amplitude outside the well (Fig. 3). At the same time the value of β_2 should be 10 or greater for the short-period wind waves and other noise for these to be thoroughly dampened by the well.

Simplifying equations (1) and (2):

$$N = \frac{3.975 \text{ X } 10^{-10} \; L_p \; D_w^2}{D_p^6} \tag{3}$$

and

$$\beta_2 = 6.244 \text{ X } 10^{-5} \; \frac{L_p \; D_w^2}{D_p^4 \; T} \tag{4}$$

for English units.

Solving for the length of pipe in feet, L_p, from equation (4):

$$L_p = 0.160 \text{ X } 10^5 \; \frac{\beta_2 \; D_p^4 \; T}{D_w^2} \quad . \tag{5}$$

The theoretical length of pipe as functions of the inside pipe diameter and the well diamater is given in Figure 4. This design is for 90 percent of the forcing wave with a period of 1 hour measured by the well. Since L_p is linearly related to period from equation (5), the pipe length from Figure 4 can be multiplied by the period (in hours) to estimate L_p required for waves other than 1 hour. To obtain 95 percent or more of a 1-hour wave, reduce the pipe length in Figure 4 by about one-half.

If the period of the important long waves is unknown, an alternate method of well design is to dampen wind waves and record any longer period waves. Curves designed to dampen 95 percent of the amplitude of a 10-second wave are presented in Figure 5. The pipe length can also be

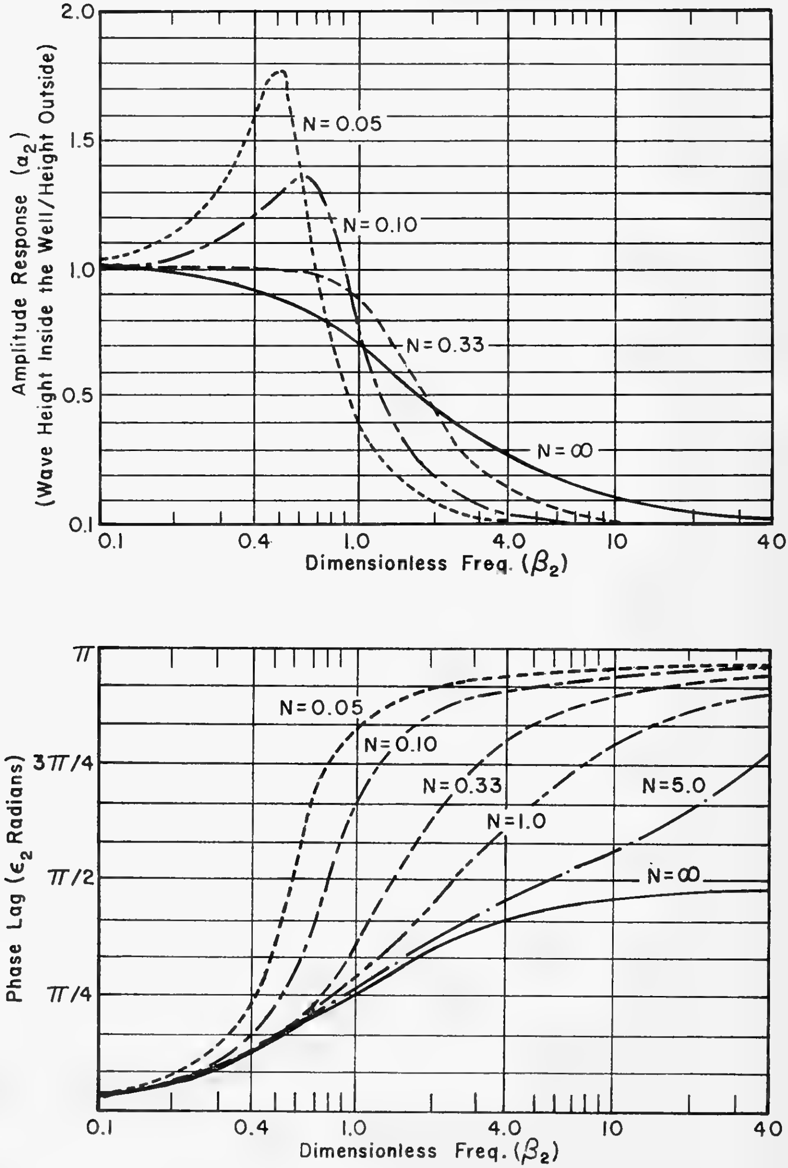

Figure 3. Response characteristics of a linear stilling well (after Noye, 1974b).

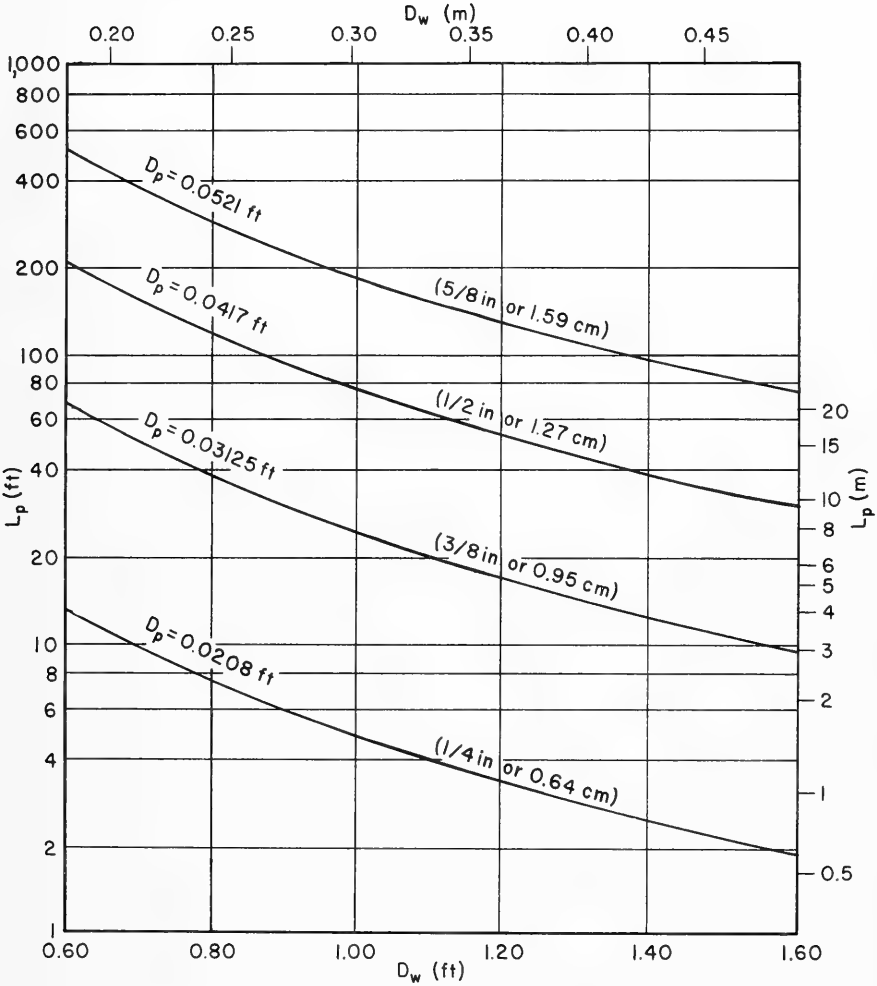

Figure 4. Theoretical linear stilling well design to obtain 90 percent of a 1-hour wave.

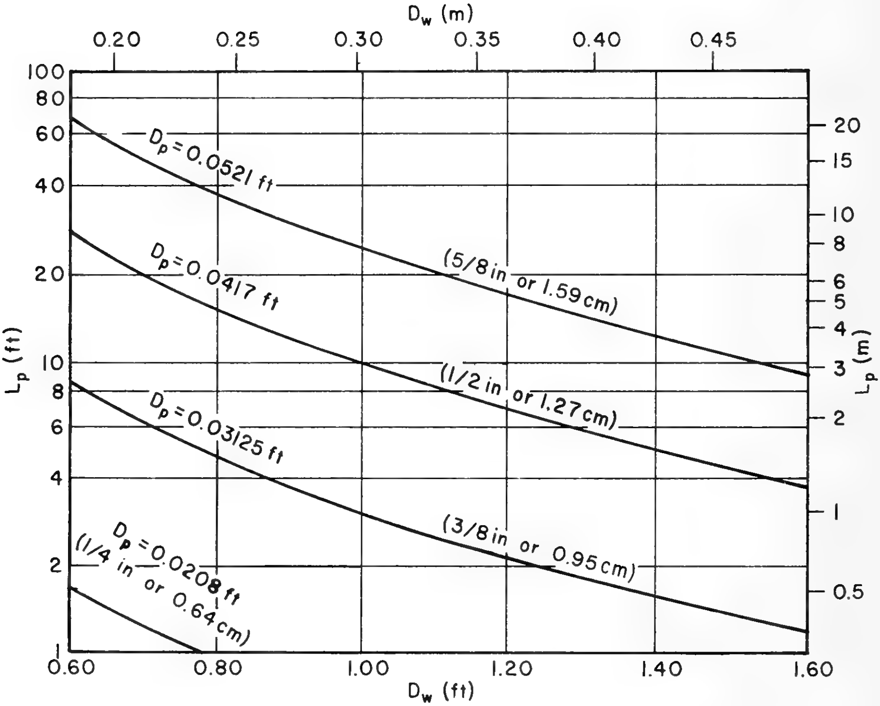

Figure 5. Theoretical linear stilling well design to dampen 95 percent of a 10-second wave.

multiplied by the period (in seconds) and divided by 10 to estimate L_p required for other than 10-second waves. The recorded long waves of interest can then be corrected for the particular well damping that occurred.

The drainage test is recommended to determine the actual hydraulic characteristics of a well designed to measure a specific long wave. If the alternate well design is used, a drainage test is unnecessary. The drainage test should be conducted after the stilling well and its components are assembled, but before the well is installed. To perform this test, partially fill the well and allow it to drain until the flow stops. Close off the orifice, then fill the well with a head of water, H (in feet), above the orifice pipe level of approximately:

$$H = \frac{8000\ \nu^2\ L_p}{g\ D_p^{\ 3}} = \frac{2.48\ X\ 10^{-7}\ L_p}{D_p^{\ 3}} \tag{6}$$

but not higher, to assure laminar flow throughout the system. Tests by Noye (1974b) show that the time constant of the well, T_o, is the time that it takes for the head inside the well to fall to 0.37 (37 percent) of it's initial head, H.

One way of determining when 37 percent of the head has been lost is by measuring the volume of water coming out of the orifice pipe with a premeasured bucket or beaker. The value of T_o is then used to determine the amplitude response, α_2 (well amplitude divided by forcing amplitude), of the well from:

$$\alpha_2 = \frac{1.0}{\sqrt{1.0 + \left(\frac{2\pi\ T_o}{T}\right)^2}}\ , \tag{7}$$

and the phase lag from:

$$\varepsilon_2 = \arctan\left(\frac{2\pi\ T_o}{T}\right) \tag{8}$$

In building a well, first determine the theoretical orifice pipe length, then build the well with a longer pipe length. Test the well several times, using the drainage test to determine the actual hydraulic characteristics of the well. If the well dampens too much of the important waves, cut off some of the orifice pipe and re-run the drainage test until the desired response characteristics are obtained.

The drainage test can be run at any time during the life of the well to determine if corrosion or other fouling has impaired the function of the well.

III. DESIGN OF THE WATER LEVEL RECORDER

Care must be taken to select a level recorder compatible with the stilling well and the waves to be measured. For economic reasons, it is

generally best to select a standard unit. A number of types with different options are available.

If a digital recorder is chosen, the sample rate should be such that at least 15 to 30 data points are taken over each important long-wave period. The level resolution should be less than one-tenth the long-wave height. Because a digital recorder makes only an instantaneous measurement at each sampling interval, it is especially important to design the stilling well to eliminate high-frequency or short-period noise.

An analog recorder should have a chart speed fast enough so each important long wave is long enough on the chart for an easy and accurate measurement. However, too fast a speed for longtime periods will lead to large volumes of paper and frequent maintenance checks to replace the chart paper. The height scale should adequately record the important waves and still allow sufficient space at the top and bottom of the chart paper to record any extreme events which may occur. Some recorders offer a reversing pen when the chart paper width is exceeded. Analog recorders are available with either strip charts or drums. Strip charts are best for long-term operation; drums may be used for a short operation on the order of 1 day. Because analog recorders record the water level continuously, some water level fluctuations shorter in period than those of interest can be allowed to propagate into the well and this noise can be eliminated when digitizing or analyzing the data.

IV. A SAMPLE DESIGN

The design of a stilling well at Pentwater, Michigan, is considered in measuring long-period waves potentially important to inlet hydraulics. A study of the Pentwater harbor indicates that waves with periods of between 1 to 2 hours will cause the largest reversing currents in the inlet (Seelig, Harris, and Herchenroder, 1976). Observation of the inlet also revealed that the water reversals have a period of about 1.5 hours. Figure 4 shows that a well with D_w = 0.83 foot (10 inches) and an orifice pipe of D_p = 0.0208 foot (0.25 inch) should have an L_p of about 7 feet to record 90 percent of a wave period, T = 1 hour, and about 11 feet for T = 1.5 hours. The well was constructed with an intake pipe length of 20 feet and several drainage tests were run. As predicted, the drainage test showed that this length dampened too much of the waves in the 1- to 2-hour range. The plastic orifice pipe was then cut back after several tries to a length of 15 feet. The drainage test showed that this well had a time constant, T_o = 500 seconds; this well was selected for the final design. The predicted response characteristics of the well from equation (7) are shown in Figure 6.

Note that for wind waves with a period of 10 seconds (0.003 hour) the amplitude response is 0.0003 which means that only 0.03 percent of wind-wave amplitudes are propagated into the well.

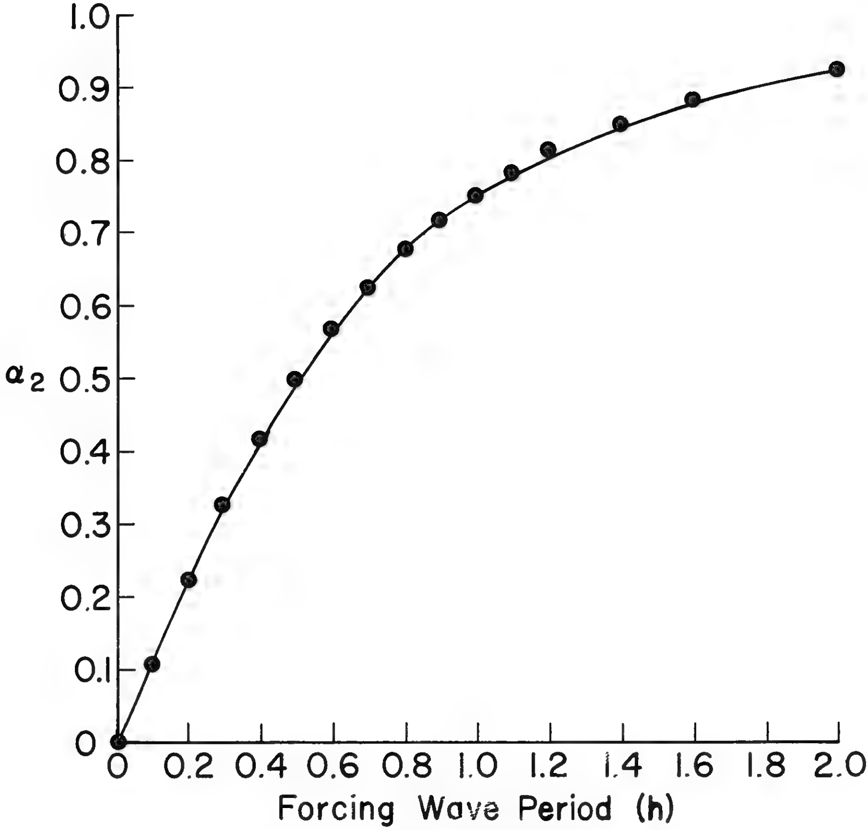

Figure 6. Amplitude response of the Pentwater stilling well predicted from the drainage test.

A further method of reducing wind-wave effects on the record inside the well is to put the orifice as deep as possible. As depth increases wave dynamic pressure attenuation increases and the wind waves become less noticeable. However, the orifice should not be put too close to the bottom where clogging may occur.

The recorder for this system was a digital recorder with a sampling interval of 5 minutes and a sampling height resolution of 0.01 foot. The float was 5 inches in diameter.

Figures 7 and 8 are examples of records and spectral analysis of records of water levels obtained at Pentwater, using this well. Note that several long waves are present simultaneously in the harbor at various periods of about 1 hour or longer. From Figure 6, 85 percent or more of the wave amplitudes are recorded and the particular percentages at each period can be used to obtain final amplitude values of the spectral components of interest.

V. CONCLUSION

A linear stilling well is recommended where accurate measurements of water level fluctuations are required and short-period noise must be dampened.

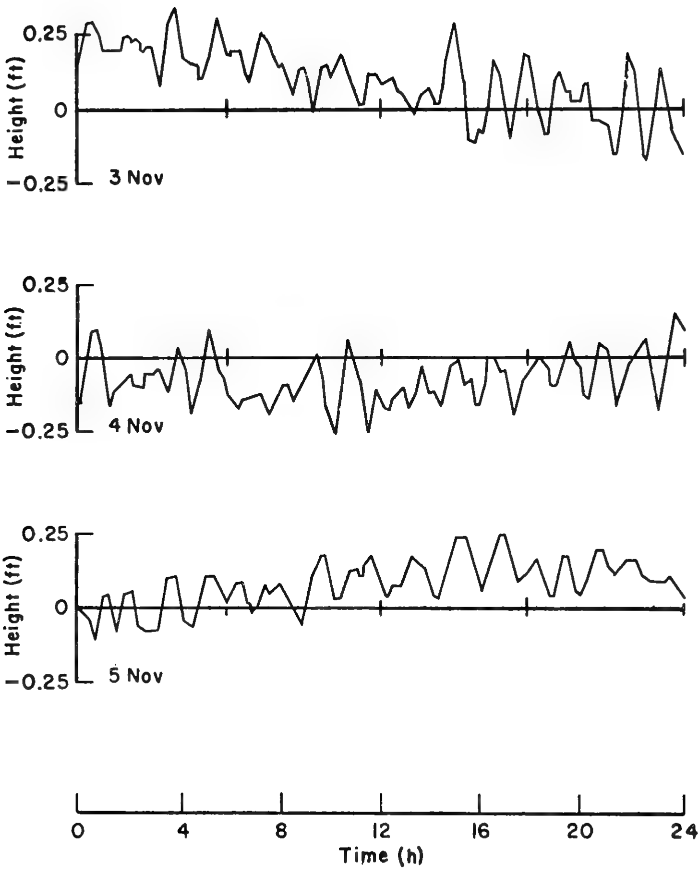

Figure 7. Pentwater water levels, November 1974.

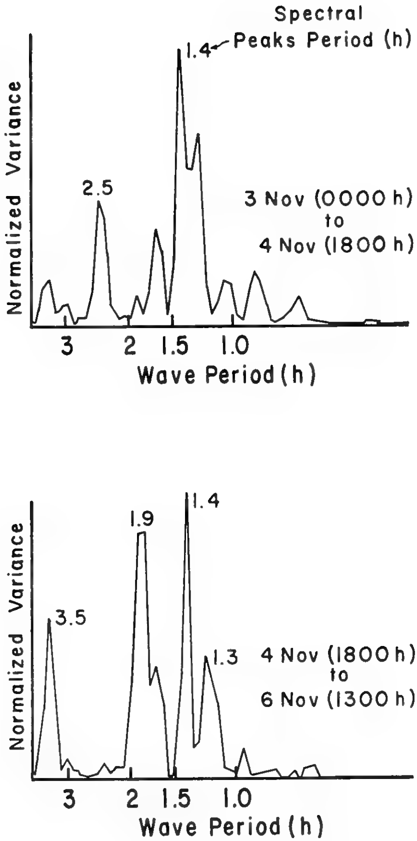

Figure 8. Spectra of water levels for Pentwater Lake, Michigan, for November 1974.

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